

On ultra-high energy cosmic rays: origin in AGN jets and transport in expanding Universe

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Abstract

The cosmic ray source spectrum produced by AGN (Active Galactic Nucleus) jets is calculated. A distinctive feature of these calculations is the account for the jet distribution on kinetic energy. The expected cosmic ray spectrum at the Earth is determined with the use of a simple numerical code which takes into account interactions of ultra-high energy protons and nuclei with the background radiation in an expanding universe.

Keywords:

ultra-high-energy cosmic rays; acceleration; propagation; AGN jets

1. Introduction

The origin of cosmic rays with energies $E > 10^{19}$ eV remains a key problem of cosmic ray astrophysics. For a uniform distribution of sources at the Hubble scale $c/H_0 \approx 3 \times 10^3 h^{-1}$ Mpc, a characteristic cutoff in cosmic ray spectrum at 5×10^{19} eV is developed (here c is the velocity of light, $H_0 = 100h$ km(s Mpc) $^{-1}$ is the Hubble parameter at the present epoch, $h = 0.7$). The cutoff arises because energetic protons lose energy by electron-positron pair and pion production (the GZK effect by Greisen (1966) and Zatsepin & Kuz'min (1966)) and energetic nuclei in addition are subject to photodisintegration (Puget et al., 1976). The observed suppression of the cosmic ray flux at energies above $\sim 5 \times 10^{19}$ eV (Abbasi et al., 2008; Abraham et al.,

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2010) confirms the presence of the GZK cutoff although the suppression due to acceleration limits in cosmic ray sources can not be excluded. A debated topic is the value of energy E_c in the range 10^{17} eV to 10^{19} eV where the Galactic component gives way to the extragalactic component in the energy spectrum of cosmic rays observed at the Earth, see Allard (2009); Berezhinsky (2009) for discussion.

The present knowledge about the highest energy cosmic rays was mainly acquired from the two major experiments HiRes (Abbasi et al., 2009; Sokolsky et al., 2010) and Auger (Abreu et al., 2010; Abraham et al., 2010). The mass composition of the highest energy cosmic rays remains uncertain. The interpretation of HiRes data favor the proton composition at energies $10^{18} - 5 \times 10^{19}$ eV, whereas the Auger data indicate that the cosmic ray composition is becoming heavier with energies changing from predominantly proton at 10^{18} eV to more heavy composition and probably reaching the pure Iron composition at about 5×10^{19} eV. The mass composition interpretation of the measured quantities depends on the assumed hadronic model which is based on not well determined extrapolation of the physics from lower energies. The found angular distributions of events exceeding 6×10^{19} eV (these particles can reach the Earth from the distances less than ~ 100 Mpc) were also different in these two experiments: the HiRes data showed the isotropic distribution; the Auger data demonstrated the correlation with AGN or objects having a spatial distribution similar to the distribution of matter in the nearby Universe with the largest excess from the region of the sky around the radiogalaxy CenA. The first data on the spectrum, composition and anisotropy from the new Telescope Array experiment support the HiRes results (Thomson, 2010).

The list of potential sources which could give the observed flux of the highest energy cosmic rays includes AGNs, gamma-ray bursts, magnetars, interacting galaxies, large-scale structure formation shocks and other objects, see e.g. review by Torres & Anchordoqui (2004).

It is assumed below that the AGN jets are the main extragalactic sources of ultra-high energy cosmic rays. The kinetic energy of an individual jet determines the maximum particle energy and the cosmic-ray power it produces. The cases of power-law and delta-shaped spectra of cosmic rays produced by an individual jet are considered. The distribution of AGN jets over the kinetic energy shapes the average source spectrum of accelerated particles. A simple numerical code is used to calculate the expected intensity of cosmic rays at the Earth.

2. Transport equations for cosmic rays

We start with a consideration of cosmic ray propagation in the intergalactic space. The approach based on the equation for cosmic ray density is appropriate for the purpose of the present research.

Let us assume a uniform distribution of cosmic ray sources in the universe. The cosmic ray number density per unit energy $N(E, t)$ and the integral number density $N(> E, t) = \int_E^\infty dE N(E, t)$ are then also uniformly distributed, i.e. does not depend on position \mathbf{r} . The total number of energetic particles in the comoving volume V is conserved and the following equation can be written down in the absence of nuclear interactions and source contribution:

$$\frac{d(V(t)N(> E, t))}{dt} = \frac{\partial(V(t)N(> E, t))}{\partial t} + \frac{dE}{dt} \frac{\partial(V(t)N(> E, t))}{\partial E} = 0 \quad (1)$$

that gives

$$\frac{\partial N(E, t)}{\partial t} + 3H(t)N(E, t) - \frac{\partial(H(t)EN(E, t))}{\partial E} = 0, \quad (2)$$

where H is the Hubble parameter and the expressions $\frac{dV}{dt} = 3HV$ and $\frac{dE}{dt} = -HE$ are used (the last equation describes the energy loss rate of ultrarelativistic particle with energy $E \approx pc$ in the expanding universe), see [Zeldovich & Novikov \(1983\)](#).

Additional terms that describe the continues energy losses $-\frac{\partial((E/\tau)N)}{\partial E}$ (if an individual particle loses energy as $\frac{dE}{dt} = -\frac{E}{\tau(E, t)}$) and the "catastrophic" particle losses of the form $\nu(E, t)N$ (that describes nuclear fragmentation or radioactive decay) can be added to the left side of Eq. (2). The source term can be added to its right side. Also, the redshift z can be introduced instead of t variable using the relation $\frac{dz}{dt} = -(1+z)H(z)$. Finally, the equation for nuclei with mass number A takes the form:

$$\begin{aligned} & -H(z)(1+z)\frac{\partial}{\partial z} \left(\frac{F(A, \varepsilon, z)}{(1+z)^3} \right) - \\ & \frac{\partial}{\partial \varepsilon} \left(\varepsilon \left(\frac{H(z)}{(1+z)^3} + \frac{1}{\tau(A, \varepsilon, z)} \right) F(A, \varepsilon, z) \right) + \nu(A, \varepsilon, z)F(A, \varepsilon, z) \\ & = \sum_{i=1,2,\dots} \nu(A+i \rightarrow A, \varepsilon, z)F(A+i, \varepsilon, z) + q(A, \varepsilon)(1+z)^m. \end{aligned} \quad (3)$$

The system of equations (3) for all kinds of nuclei with different A should be solved simultaneously. The energy per nucleon $\varepsilon = E/A$ is used here because it is approximately conserved in a process of nuclear photodisintegration (analogously to a standard practice employed in the studies of cosmic ray nuclear spallation in the interstellar gas, see Berezhinskii et al. (1990)), $F(A, \varepsilon, z)$ is the corresponding cosmic-ray distribution function, $q(A, \varepsilon)$ is the density of cosmic-ray sources at the present epoch $z = 0$, m characterizes the source evolution (the evolution is absent for $m = 0$), $\tau(A, \varepsilon, z)$ is the characteristic time of energy loss by the production of e^-e^+ pairs and pions, $\nu(A, \varepsilon, z)$ is the frequency of nuclear photodisintegration, the sum in the right side of Eq. (3) describes the contribution of secondary nuclei produced by the photodisintegration of heavier nuclei, $H(z) = H_0((1+z)^3\Omega_m + \Omega_\Lambda)^{1/2}$ is the Hubble parameter in the flat expanding universe with the matter density $\Omega_m (= 0.3)$ and the Λ -term $\Omega_\Lambda (= 0.7)$.

We used Eq. (3) for calculations of cosmic-ray flux produced by galaxy cluster accretion shocks (Ptuskin et al., 2009) and earlier for calculations of proton fluxes generated by different distributions of cosmic ray sources (Ptuskin et al., 2003). The analogous equations were recently used by (Aloisio et al., 2010). The analytic study of the process of transformation of cosmic-ray composition described in (3) by the terms with frequencies ν was conducted by Hooper et al. (2008). They reproduced some mathematical results known in the theory of nuclear transformation caused by the spallation reactions in the interstellar gas, see Berezhinskii et al. (1990). Notice that usually the authors prefer to build up an expression for energetic particle or photon density in the expanding universe without explicit writing down equations like (3), see e.g. basic monographs Stecker (1971); Berezhinskii et al. (1990). Excellent discussion on the description of cosmic ray propagation was presented by Berezhinsky et al. (2006).

Eq. (3) are valid for an arbitrary regime of cosmic ray propagation - diffusion, rectilinear motion, or any intermediate regime. In the case of rectilinear propagation, all functions in Eq. (3) may have the direction of particle motion (determined by the unit vector $\frac{\mathbf{v}}{v}$) as an additional independent variable that allows studying some models with anisotropic source distribution.

The photodisintegration by the background radiation is calculated in the present work in the approximation used by Karakula & Tkaczyk (1993). The corresponding cross sections are mainly taken from the works Puget et al. (1976); Rachen (1996); Khan et al. (2005). The spectra of the background microwave, infrared and optical radiation are taken from Malkan & Stecker

(1998). The numerical solution of the cosmic-ray transport equations follows the finite differences method. The variables are the redshift z and $\log(E/A)$. The computation starts from some maximum z ($z_{max} = 2$ was assumed in our calculations) and goes in the direction of decreasing redshift till the present epoch $z = 0$. At any given z , the computation starts from some maximum energy per nucleon and goes to smaller energies and to smaller atomic numbers A from Iron to Hydrogen.

It should be emphasized that an alternative Monte Carlo techniques were used for treating the photodisintegration of ultra-high energy cosmic rays. A representative list of references was given by Hooper et al. (2008), see also Allard et al. (2008); Allard (2009); Hooper & Taylor (2010) where the important results on expected cosmic ray spectra for different source spectra and compositions were obtained. Although more sophisticated in treating details of nuclear interactions, the Monte Carlo techniques are more time consuming compared to the solution of Eq.(3) by the finite differences method and should be used when it is required by the specific characteristics of the problem under consideration.

The assumption of continuous source distribution is not valid when particles lose energy at a scale less than the distance between cosmic ray sources. The finite distance to the nearest source is approximately taken into account in our calculations by the cutoff of the source distribution at $z_{min} \approx 0.48H_0d/c \ll 1$, so that $q = 0$ at $z \leq z_{min}$ ($0.48d$ is the average distance of an observer to the nearest source if the point sources arrange the cubic lattice with the edge, the distance between sources, equals to d). The statistically uniform source distribution is assumed at larger redshifts. The rectilinear propagation of cosmic rays from the close source is accepted here but different modes of cosmic ray propagation can be modelled by changing the relation between z_{min} and d .

The imposition of an arbitrary intergalactic magnetic field does not affect the uniform isotropic distribution of cosmic rays. The account of cosmic-ray source granulation makes important the presence of extragalactic magnetic fields. Magnetic effects depend on the gyro-radius $r_g = 10(E/10^{19}\text{ZeV})(B/10^{-9}\text{G})^{-1}$ Mpc that determines the deflection of ultrarelativistic particle. In principle, the presence of magnetic field changes angular distribution of cosmic rays and cause cosmic rays to propagate over longer distances than the straight line distance. The weak influence of intergalactic fields on the cosmic ray intensity was found in MHD simulations of large-scale structures by Dolag et al. (2004). Different conclusion was reached by Sigl et al. (2004). It is clear

that results critically depend on the assumptions about the strength and structure of the intergalactic magnetic field, see also (Parizot, 2004; Kotera & Lemoine, 2008; Das et al., 2008). Some of magnetic field effects can be investigated in the diffusion approximation (Berezinsky et al., 2006; Berezhinsky & Gazizov, 2007) (additional diffusion terms should be added then to the transport equations). The most straightforward but time consuming is the direct calculation of possible trajectories in extragalactic magnetic fields from a source to an observer. The corresponding Monte Carlo code by Sigl et al. (2004) is available on the web. It is worth to emphasize again that the main problem in such kind calculations is the uncertainties in the strength and structure of extragalactic magnetic fields.

The objective of our paper, the determination of the basic overall shapes of cosmic ray spectrum at the Earth for different source functions produced by the AGN jets, does not require more complicated computational procedure than solution of Eqs (3) with a source distribution cutoff at some z_{min} .

3. Spectrum of ultra-high energy cosmic rays accelerated in AGN jets

Simple estimates (Torres & Anchordoqui, 2004; Berezhinskii et al., 1990) show that from the viewpoint of energetics the AGN jets can be the sources of ultra-high energy cosmic rays. Different aspects of particle acceleration in AGN jets were considered by Biermann & Strittmatter (1987); Norman et al. (1995); Biermann et al. (2008); Lemoine (2008); Pe’er et al. (2009), see also references below.

To maintain the cosmic ray intensity observed in the Auger experiment at energies above 10^{19} eV, the power of extragalactic sources of the order of 3×10^{36} erg s $^{-1}$ Mpc $^{-3}$ is required. This value increases if the contribution of cosmic rays with smaller energies is taken into account. At the same time the AGN jets release kinetic energy at the level of 3×10^{40} erg s $^{-1}$ Mpc $^{-3}$ and approximately 6% of this energy is contained in the jets with a power $L_{jet} = 10^{44} - 10^{46}$ erg s $^{-1}$ characteristic of FR II (Fanaroff-Riley II) radiogalaxies and radio loud quasars. We shall use the notation FII for this population of jets. The numerous and less powerful jets of low-luminosity AGN have power $L_{jet} = 10^{40} - 10^{44}$ erg s $^{-1}$. We shall denote them as FI sources.

Without specifying the mechanism of particle acceleration in jets, one can use the Hillas criterion $E_{max} = Ze\beta Bl$ for the estimate of maximum

energy which the particles with charge Ze in the acceleration region of size l , magnetic field strength B , and the velocity of magnetic field transport $u = \beta c$ can gain (Hillas (1984), see also Ptitsyna & Troitsky (2010)).

Let us consider the "optimistic" estimate and assume that the energy flux of a statistically isotropic magnetic field frozen in the jet is related to the kinetic energy flux by the relation $L_{jet} = \beta c \frac{B^2}{6\pi} \pi R^2$. The equality $R = l/2$ is accepted here for the jet radius; the jet velocity is βc . As a result, the following estimate of the maximum energy of accelerated particles can be obtained:

$$E_{max} = Ze (6\beta c^{-1} L_{jet})^{1/2} \approx 2.7 \times 10^{20} Z \beta^{1/2} L_{jet,45}^{1/2} eV, \quad (4)$$

where $L_{jet,45} = L_{jet} (10^{45} \text{ erg s}^{-1})^{-1}$, see Lovelace (1976); Blandford (1993); Aharonian et al. (2002); Waxman (2004); Farrar & Gruzinov (2009) and references therein for the derivation of similar formulas.

The expression for E_{max} can be also derived based on the well studied case of the diffusive shock acceleration in young supernova remnants. Let us consider a jet which consists of the proton-electron plasma with the mass density ρ and the power $L_{jet} = 0.5 \rho u^3 \pi R^2$. The cosmic rays are accelerated at the jet termination shock and their energy density is $w_{cr} = \eta_{cr} \rho u^2$, where $\eta_{cr} \approx 0.1$. The magnetic field at the site of acceleration can reach the value of the order $B = (4\pi \beta w_{cr})^{1/2}$ if the field is amplified by the strong cosmic-ray streaming instability (Bell, 2004). The maximum energy of accelerated particles is $E_{max} = Ze \beta B R$ if the Bohm diffusion near the shock is assumed (note that this E_{max} satisfies the Hillas criterium). It finally gives $E_{max} \approx Ze \beta (8\eta_{cr} c^{-1} L_{jet})^{1/2}$ that is close to the estimate (4). We shall use Eq. (4) and set $\beta = 1$ in the calculations below.

We consider two types of cosmic-ray source spectrum ejected into the intergalactic space. The first type is a delta function spectrum and the corresponding source power is $q_d = \xi_{cr} n_{jet} L_{jet} E_{max}^{-1} \delta(E - E_{max})$, where the coefficient ξ_{cr} characterizes the fraction of jet kinetic energy that goes to the accelerated particles; n_{jet} is the jet number density in the intergalactic space. The second type of sources has a power law spectrum $\propto E^{-2}$ and the corresponding source power is $q_p = \xi_{cr} n_{jet} L_{jet} E^{-2} H(E_{max} - E)$, where $H(x)$ is the step function. (Strictly speaking, the additional logarithmic normalization factor $(\ln(E_{max}/E_{min}))^{-1}$ should be included in the last expression for q_p . We omit it because of uncertain value of the minimal energy E_{min} for particles ejected from the accelerator.)

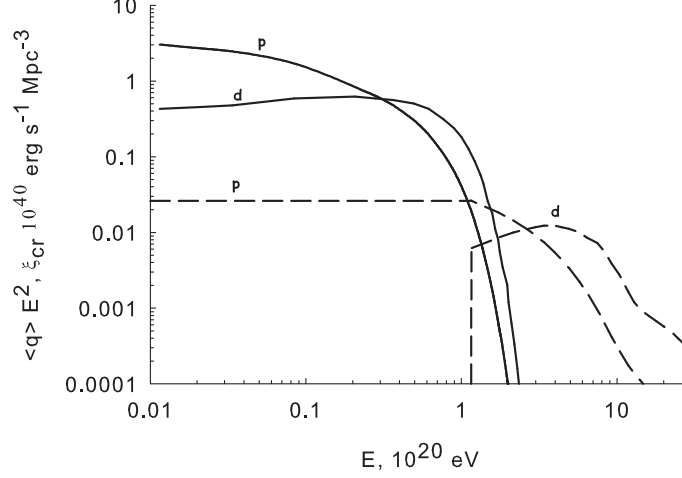


Figure 1: Calculated average source spectra of jet populations FI (solid lines) and FII (dash line) for delta-function (d) and power law E^{-2} (p) cosmic ray spectra generated by individual jets. Eq. (4) was used for calculations of $E_{max}(L_{jet})$

It can be recalled as an example that both spectrum shapes of ejected particles arise in the consideration of diffusive shock acceleration in supernova remnants, see [Ptuskin & Zirakashvili \(2005\)](#). The runaway particles have close to the delta function energy spectrum $\sim \delta(E - E_{max})$ where E_{max} is the maximum energy of accelerated particles that is achieved at the given stage of a supernova shock evolution. The energetic particles that remains confined inside the remnant may have close to a power law spectrum and leave out into the interstellar medium at some stage of SNR evolution when the shock breaks up. It should be stressed that we do not assume that two discussed injection spectra work at the same time and analyze them separately.

The source functions $q_d(E)$ and $q_p(E)$ should be averaged over the distribution of jet luminosity $n_{jet}(L_{jet})$ to obtain the average source function of extragalactic cosmic rays. The results are shown in Fig. (1) for the functions $n_{jet}(L_{jet})$ presented by [Koerding et al. \(2008\)](#) in their Figure (8) for the kinetic luminosity function of jets. Four source functions in Fig. (1) correspond to the combination of two populations of jets, FI and FII, and two types of jet spectra, d and p . These four source functions are considered here

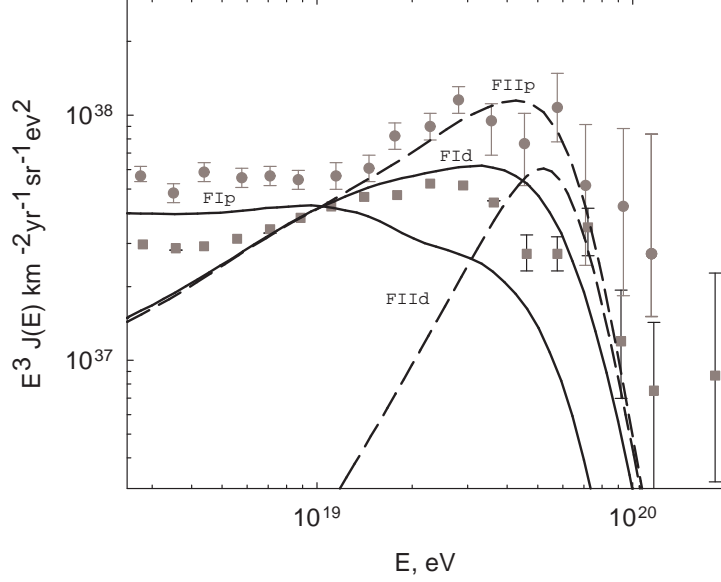


Figure 2: Calculated spectra of extragalactic cosmic rays for sources $\langle q_d \rangle$ and $\langle q_p \rangle$ averaged over the AGN jet population FI (solid lines FIId and FIp) and FII (dash lines FIId and FIIp). The spectra (except FIId) are normalized to the intensity observed at 10^{19} eV in the Auger experiment. Data are from HiRes experiment (Abbasi et al., 2009) (circles) and Auger experiment (Abraham et al., 2010) (squares).

as representing four different scenarios of cosmic ray acceleration in jets.

We solved numerically the set of transport Eqs (3) for the described types of the average source spectrum. Fig. (2) illustrates the results. It was assumed that the source chemical composition coincides with the composition of Galactic cosmic ray sources. The spectra were normalized at 10^{19} eV to the observed by Auger intensity. It requires very different efficiency of particle acceleration $\xi_{cr,FII}/\xi_{cr,FI} \sim 20$ in the FII and FI jets. These efficiencies are $\xi_{cr,FII} \sim 0.1$ and $\xi_{cr,FI} \sim 0.005$ if the source spectra are extrapolated down to 1 GeV. No cosmological evolution was assumed in our calculations ($m = 0$). The evolution is different for different morphological types of AGN, see e.g. Berezhinsky et al. (2006), but it does not significantly affect the calculated spectra at energies $> 3 \times 10^{18}$ eV since these particles may come from the distances not larger than about 2×10^3 Mpc.

Of four spectra shown in Fig. (2), two reproduce cosmic ray observations

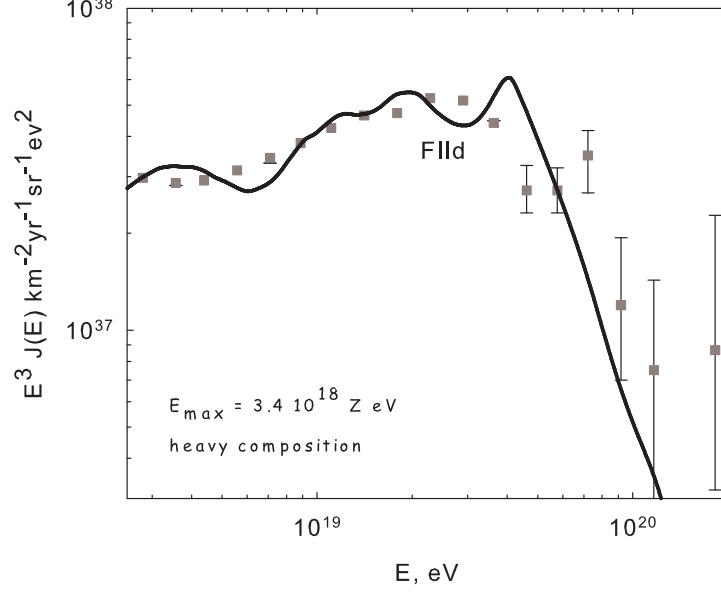


Figure 3: Calculated spectrum of extragalactic cosmic rays for sources $\langle q_d \rangle$ averaged over the AGN jet population FIId with heavy composition; E_{max} is decreased by 80 compared to Eq. (4). Data are from Auger experiment (Abraham et al., 2010) (squares).

with reasonable accuracy. They correspond to the AGN jet population FI with delta-function source spectra and the AGN jet population FII with power-law spectra E^{-2} .

The finite distance z_{min} to the closest to an observer source was taken into account as discussed in the preceding Section. This distance is a function of particle energy and charge and is different for the source populations FI and FII. The absence of sources at distances < 90 Mpc in our model resulted in a steeply sloping down spectrum of cosmic rays at the highest energies 10^{20} eV for the FII source distribution.

The dependence $n_{jet}(L_{jet})$ together with Eq. (4) for $E_{max}(L_{jet})$ leads to the dependence of cosmic-ray source number density on particle energy $n_s(E)$. For FI population of sources with delta shaped spectra, the source density is $n_s = 10^{-4}$ Mpc $^{-3}$ at $E = 6 \times 10^{19}$ eV and $n_s = 2 \times 10^{-3}$ Mpc $^{-3}$ at $E = 10^{19}$ eV that coincides with the results of Takami & Sato (2009) derived from the analysis of cosmic-ray arrival direction distribution.

Protons dominate in the calculated composition of cosmic rays that is in

strong disagreement with the Auger data. To get out of a difficulty one can take anomalously high abundance of heavy nuclei and reduce the maximum particle energy at the source (Allard, 2009; Hooper & Taylor, 2010). We reserve the consideration of this issue for a later paper and show in Fig. (3) only one example of calculations where the shape of source spectrum corresponds to the FIId sources with the maximum particle energy E_{max} decreased by a factor of 80 compared to the "optimistic" estimate (4) (this relieves the extreme assumptions used in the derivations of Eq. (4)) and the Iron abundance at the source comprises 1/3 of all nuclei. The calculated cosmic-ray spectrum only roughly reproduce the observed spectrum. The cosmic-ray composition can be characterized by the mean logarithmic atomic number $\langle \ln(A) \rangle$. Its calculated value rises approximately linearly from about 0.25 at 5×10^{18} eV to 3.7 at 5×10^{19} eV in a qualitative agreement with the Auger data on the shower maximum dependence on energy.

4. Conclusions

It is believed that the particle acceleration by jets in active galactic nuclei is the most efficient source of cosmic rays with the highest energies, $E > 10^{19}$ eV. In the present work we distinguish two populations of jets: FI produced by the low luminosity AGN populations with jet power 2×10^{40} to 3×10^{44} erg s⁻¹, and FII produced by high luminosity AGN with jet power larger than 2×10^{44} . The corresponding jet distributions on power were given by Koerding et al. (2008).

The typical power law spectrum of nonthermal jet radiation implies the power law particle spectrum of the form close to E^{-2} . One may expect that the spectrum of particles released into the extragalactic space, the source spectrum of extragalactic cosmic rays, has the same shape. Another possibility is that accelerated particles remains confined inside the source and only particles with maximum energies run away into intergalactic space so that the source spectrum is of a delta-shaped form. The average source spectrum of extragalactic cosmic rays is determined as the convolution of one of these source functions of an individual jet with the jet distribution on power. Based on the Hillas criterion, we accepted an optimistic estimate for the maximum energy of accelerated particles (4) with its characteristic scaling $E_{max} \propto L_{jet}^{1/2}$ and used it in our calculations.

The computations of cosmic ray propagation in the expanding Universe filled with the background electromagnetic radiation were fulfilled by the

use of a simple numerical code which solves the system of coupled transport Eqs (3) for energetic protons and nuclei from He to Fe. The calculations were made under the approximation of continuous energy losses by e^- , e^+ and pion production and the "catastrophic" losses through photodisintegration and corresponding production of secondary nuclei.

The results of our calculations are illustrated in Fig. (2). The observed spectrum of ultra-high energy cosmic rays can in principle be explained in the frameworks of two scenarios - the acceleration by the FI sources with individual jet spectra of the delta-shaped form or the acceleration by the FII sources with individual jet spectra close to E^{-2} form. The transition from Galactic to extragalactic component in the observed at the Earth spectrum occurs at about $(3...5) \times 10^{18}$ eV.

The calculated spectra are normalized to the observed by Auger intensity at 10^{19} eV. It requires very different efficiencies of transformation of the jet kinetic energy to the energy of cosmic rays in the FII and FI sources: $\xi_{cr,FII}/\xi_{cr,FI} \sim 20$. It was assumed that the elemental composition of accelerated particles is the same as in the Galactic cosmic-ray sources. This results in the predominantly proton composition of ultra high energy extragalactic cosmic rays that is compatible with the HiRes data but not with the Auger data. One needs to significantly increase the abundance of heavy nuclei at the source and drastically decrease the value of E_{max} to fit the Auger data (Allard, 2009; Hooper & Taylor, 2010). This procedure was discussed at the end of Section 3 and illustrated by Fig. 3.

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